# ICT.H409

# Optics in Information Processing

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## “Let there be light”

Visual information is one of the most important clues for human communication.

In information and communication technology, digital images and videos play a crucial role.

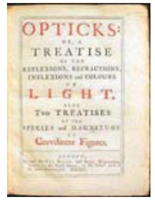
“Light” is the carrier of visual information.

This is the reason why we need to learn “light.”



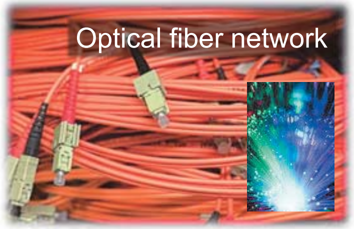
## Optics in information processing

### Light as information carrier




I. Newton, Opticks: or, a treatise of the reflexions, refractions, inflexions and colours of light

Camera / Sensor




Display
User Interface

Human vision



[Course description]

Starting with the physical meaning of digital image information, the relation between radiometry and photometry is discussed.

Next, the fundamental knowledge required for understanding image acquisition, processing, and display systems is explained, such as geometrical optics and aberration theory, basics of wave optics, Fourier analysis of optical imaging systems.

According to this theoretical background, the characteristics of an imaging system is discussed, such as the resolution and the depth of field of an imaging system, along with the examples of digital camera, video, and microscope.

In addition, the basic theory of color science is introduced along with the application to the color imaging and display.

Finally, the principle and limitations of 3D image acquisition and display technology are discussed based on the knowledge of geometrical and wave optics.

## What we will learn in this course

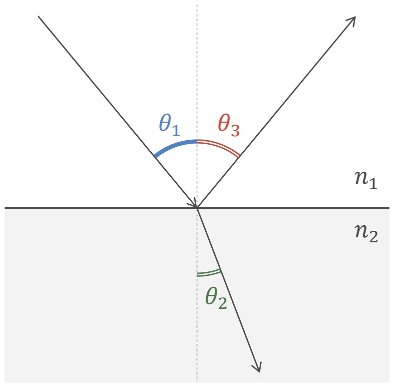
- Theoretical background of optics and digital image acquisition, processing, and display systems.
  - E.g., Digital Still Camera, Camcoder, Digital Television, Video systems, Image scanner, Displays, Printers, Microscopy, Optical measurement, Stereoscopic displays, holography
  - Imaging through lens system, Color imaging, Multispectral imaging, 3D imaging
- Some recent R&D topics in optical imaging and image processing.

## What we will NOT learn in this course:

- Software and hardware implementation methods of digital image processing.
- Technology details of each items.



## Let's recall the knowledge of optics...




$\theta_1$: Incident angle
$\theta_2$: Refraction angle
$\theta_3$: Reflection angle

**Reflection formula**

**Quiz 1.1**
What is the relation between $\theta_3$ and $\theta_1$?

**Refraction formula**

**Quiz 1.2**
What is the relation between $\theta_2$ and $\theta_1$?



Radiometry and Photometry
- The optical information perceived by human vision and imaging device

Geometrical optics, lens aberration.
- Basic concept of optical system design

Interference, diffraction, and Fourier optics
- What is happening between object and observation, from the aspect of physical optics.

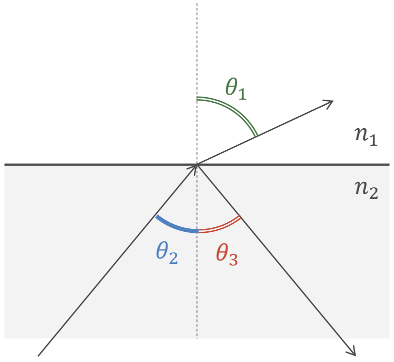
Imaging system analysis based on wave optics,
Frequency analysis of imaging systems, resolution limit, OTF, MTF.
Numerical aperture (NA) of an imaging system,
Depth of focus, depth of field
- Characteristics and limitations of the imaging system using lens.

Color information in images, color display
- How does human vision perceive color? How does an imaging system capture and display color?

3D image acquisition and display
- What is 3D optical information? How to capture? How to reproduce?



## Refraction of light incident from dense medium to less dense medium




$\theta_2$: Incident angle
$\theta_1$: Refraction angle
$\theta_3$: Reflection angle

When $n_2 > n_1$

**Quiz 1.3**
What is the condition that the refracted light disappears?

$\sin\theta_1 = \frac{n_2}{n_1}\sin\theta_2 \leq 1 \Rightarrow \sin\theta_2 \leq \frac{n_1}{n_2}$

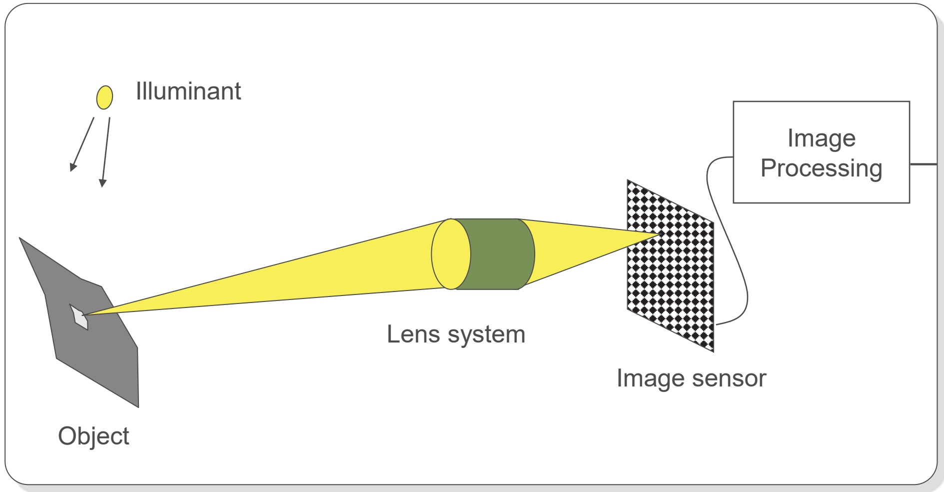
If $\theta_2 > \theta_c$, no refracted light appears.

$\sin\theta_c = \frac{n_1}{n_2}$

$\theta_c$: Critical angle

Total reflection (total internal reflection).

# What is the information acquired by an imaging system?

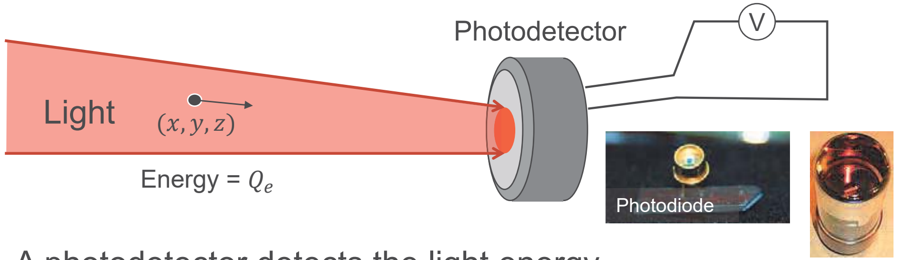





# Radiometry and photometry



# Detection of light




Photomultiplier tube

A photodetector detects the light energy.

The energy flow per unit time passing through a point $(x, y, z)$ in a direction $(\theta, \phi)$ is called **radiant flux**.

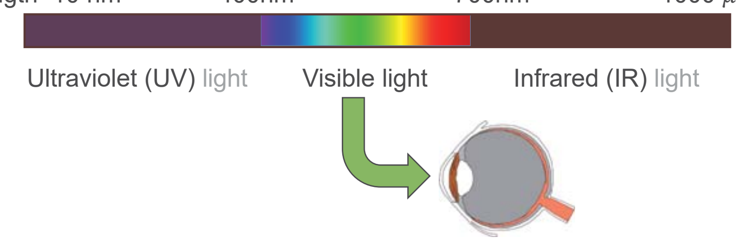
**Radiant flux** $\Phi(x, y, z, \theta, \phi)$ [W]





# Is light measured in energy?

Wavelength 10 nm ~ 400nm ~ 700nm ~ 1000 $\mu$m

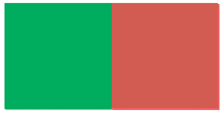


Ultraviolet (UV) light Visible light Infrared (IR) light

UV and IR lights are invisible. → Measured in energy.

In case of visible light, the measurement of light should be connected with the human perception of brightness.

# Same energy but different brightness



## Different wavelength but same brightness

Different energy

$\Phi_e(\lambda_1) \cdot V(\lambda_1)$
$\Phi_e(\lambda_2) \cdot V(\lambda_2)$
} same brightness

Mixture of light with multiple wavelengths

$\Phi_e(\lambda_1) \cdot V(\lambda_1)$
$\Phi_e(\lambda_2) \cdot V(\lambda_2) + \Phi_e(\lambda_3) \cdot V(\lambda_3)$
} same brightness

Photoshop Lab
72 -61 59
64
56
50
47
43
38
35
47 60 39



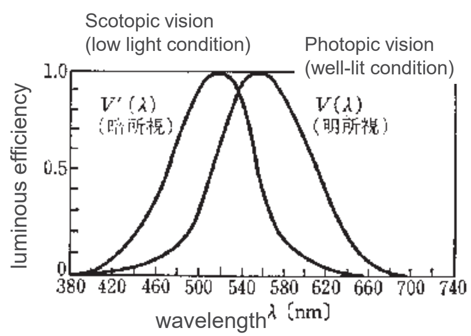
# Photometric quantity of light

$V(\lambda)$: Spectral luminous efficiency of human vision

$$\Phi_v = K_m \int \Phi_e(\lambda)\, V(\lambda)\, d\lambda$$

$\Phi_e(\lambda)$: Spectral radiant flux [W]

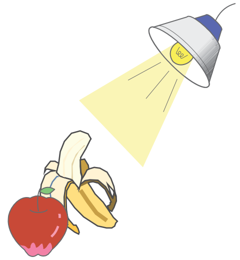
$\Phi_v$: Luminous flux [lm]




Maximum luminous efficacy @555nm
$K_m$ = 683 lm·W$^{-1}$



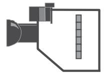
# Spectral sensitivity (Disregarding color)



$V(\lambda)$

Human vision

$$Y = \int \Phi_e(\lambda)\, V(\lambda)\, d\lambda$$



$S(\lambda)$

Photodetector
Image sensor

$$g = \int \Phi_e(\lambda)\, S(\lambda)\, d\lambda$$



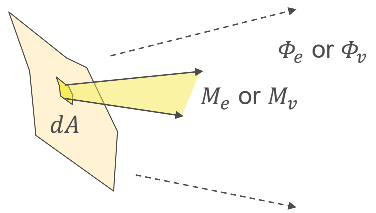
# Radiant and luminous quantities

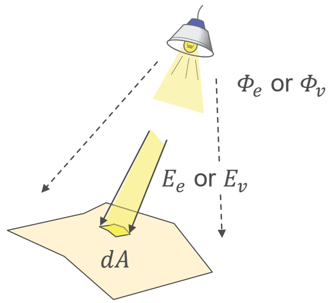
- Radiant quantities: physical
- Luminous quantities: psychophysical, related to the stimuli to the human vision

| Radiant quantities | | Definition | Unit | Luminous quantities | | Definition | Unit |
|---|---|---|---|---|---|---|---|
| Radiant Energy | $Q_e$ | Energy emitted or transmitted from an object | J | Quantity of light | $Q_v$ | $\int \Phi_v dt$ | lm·s |
| Radiant flux | $\Phi_e$ | $\frac{dQ_e}{dt}$ | W | Luminous flux | $\Phi_v$ | $K_m \int \Phi_e(\lambda) V(\lambda) d\lambda$ | lm |
| Radiant exitance | $M_e$ | $\frac{d\Phi_e}{dA}$ | W·m$^{-2}$ | Luminous exitance | $M_v$ | $\frac{d\Phi_v}{dA}$ | lm·m$^{-2}$ |
| Irradiance | $E_e$ | $\frac{d\Phi_e}{dA}$ | W·m$^{-2}$ | Illuminance | $E_v$ | $\frac{d\Phi_v}{dA}$ | lm·m$^{-2}$ lx |
| Radiant intensity | $I_e$ | $\frac{d\Phi_e}{d\Omega}$ | W·sr$^{-1}$ | Luminous intensity | $I_v$ | $\frac{d\Phi_v}{d\Omega}$ | lm·sr$^{-1}$ cd |
| Radiance | $L_e$ | $\frac{d^2\Phi_e}{dA d\Omega \cos\theta}$ | W·m$^{-2}$ ·sr$^{-1}$ | Luminance | $L_v$ | $\frac{d^2\Phi_v}{dA d\Omega \cos\theta}$ | cd·m$^{-2}$ |

E.g., 40W Fluorescent Lamp: Luminous flux ≅ 3000 lm, Luminance ≅ 9000 cd·m$^{-2}$
Normal desktop irradiance ≅ 300lx
Luminous intensity of *x* W Incandecent lamp ≅ *x* cd

# Flux per unit area




Radiant exitance $M_e$ [W·m$^{-2}$]

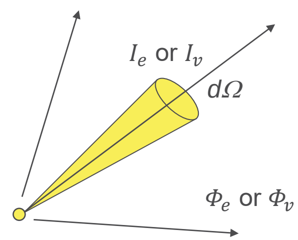
Luminous exitance $M_v$ [lm·m$^{-2}$]

Irradiance $E_e$ [W·m$^{-2}$]

Illuminance $E_v$ [lm·m$^{-2}$] [lux]



# Flux per unit solid angle



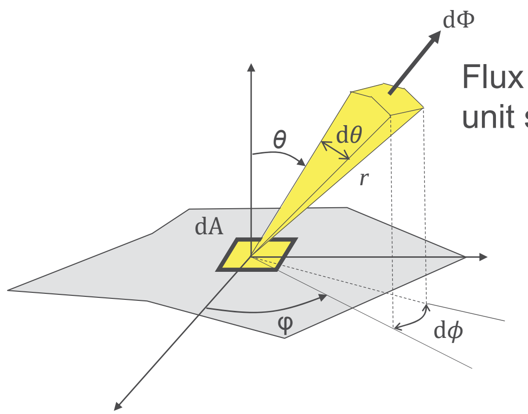

Radiant intensity $I_e$ [W·sr$^{-1}$]

Luminous Intensity

$I_v$ [lm·sr$^{-1}$] [cd]



# Emission or radiation at a surface



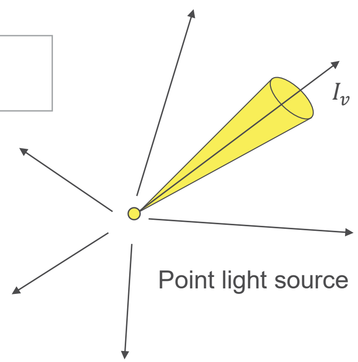

Flux per unit area and unit solid angle

Radiance $L_e$ [W·m$^{-2}$·sr$^{-1}$]

Luminance $L_v$ [cd·m$^{-2}$]

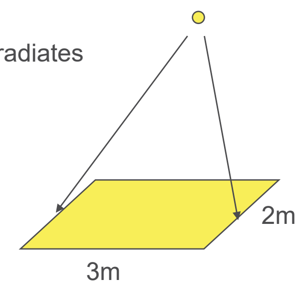


**Q1.4** A point source emits uniformly into all space with a total power 660 lm. What is the luminous intensity?

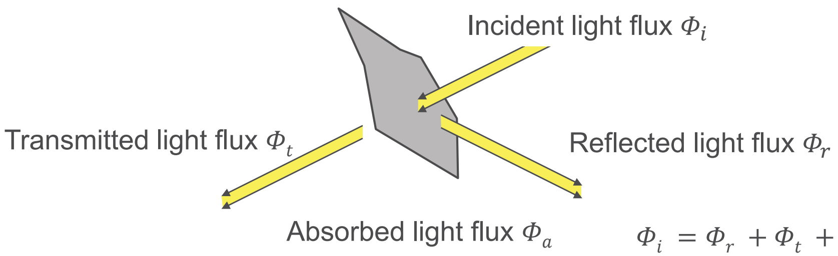




**Q1.5** A point source with a total power 660 lm irradiates a rectangular area of 3m × 2m .
What is the illuminance of the irradiated area?



# Reflection, transmission, and absorption




$$\Phi_i = \Phi_r + \Phi_t + \Phi_a$$

Reflectance: $\rho = \dfrac{\Phi_r}{\Phi_i}$

Transmittance: $\tau = \dfrac{\Phi_t}{\Phi_i}$

Optical density

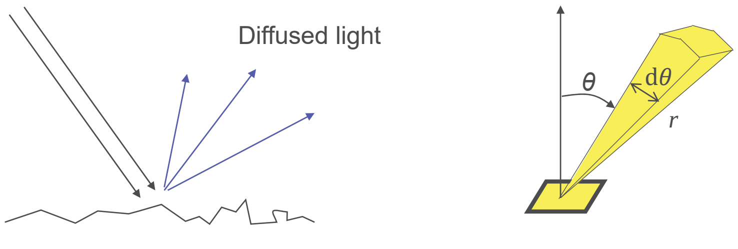
Reflectance density: $D_\rho = -\log_{10} \rho = \log_{10} \dfrac{\Phi_i}{\Phi_r}$

Transmittance density: $D_\tau = -\log_{10} \tau = \log_{10} \dfrac{\Phi_i}{\Phi_t}$

Absorbance: $a = -\log_{10} \dfrac{\Phi_a}{\Phi_i}$



# Reflection at diffuse surface

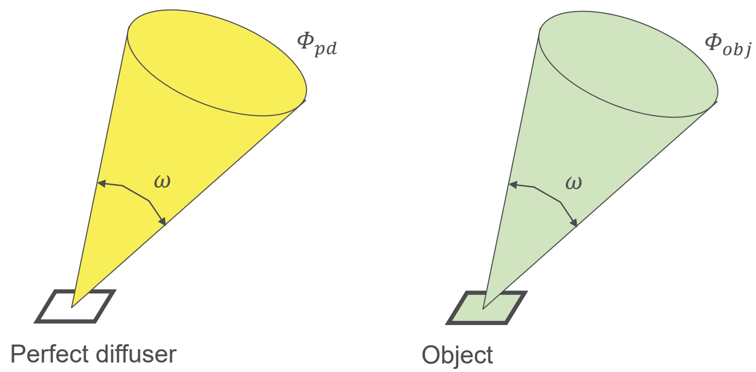



## Lambertian surface, Lambertian source

The radiance or luminance is constant in all directions.
The radiant intensity or luminous intensity is proportional to $\cos\theta$.
The lambertian surface that reflects 100% of incident light is called "perfect diffuser."



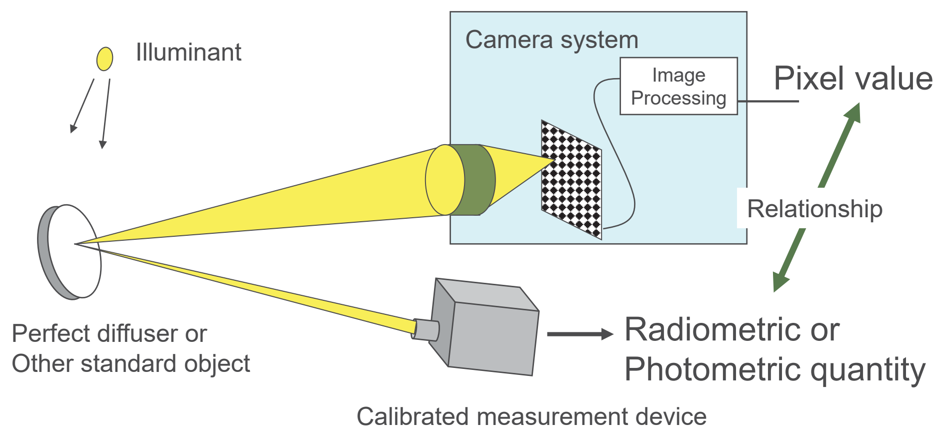
# Reflectance factor (transmittance factor, radiance factor)



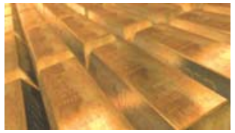

$$\text{Reflectance factor} = \frac{\Phi_{obj}}{\Phi_{pd}}$$

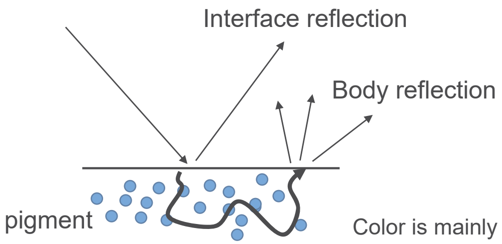


# Calibration of a camera to photometric or radiometric quantity



# What is happening at an object's surface?






Color is mainly caused by body reflection.
Except for metals.

Interface reflection = specular component
+ diffuse component (surface roughness)

Body reflection = diffuse reflection

Reflected light = specular component + diffuse component



# Summary

- Optics in imaging and video technology,
- Reflection and refraction
- Radiometry and photometry.
  - Radiant flux, luminous flux
  - Radiant intensity, luminous intensity
  - Irradiance, illuminance
  - Radiance, luminance
- Reflectance, transmittance, optical density
- BRDF



# Bidirectional reflectance distribution function (BRDF)

$$BRDF(\theta_i, \phi_i; \theta_r, \phi_r)$$

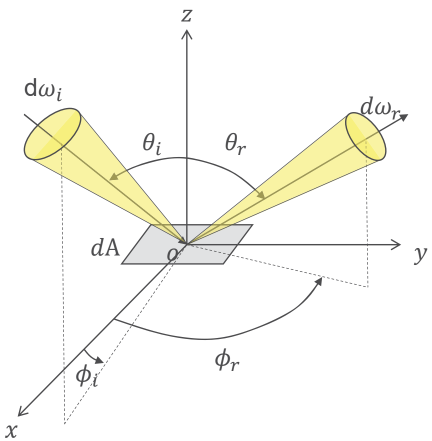
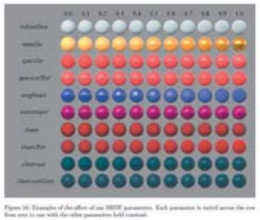



Figure 1: Images slices of MERL 100 BRDFs.




Physically-Based Shading at Disney
by Brent Burley, Walt Disney Animation Studios, SIGGRAPH 2012

シュガー・ラッシュ